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Dither-free stabilization of a femtosecond doubly resonant OPO using parasitic sum-frequency mixing

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Stable operation of a doubly resonant femtosecond optical parametric oscillator (OPO) requires submicron matching of the OPO and pump laser cavity lengths, which is normally implemented using a dither-locking feedback scheme. Here we show that parasitic sum-frequency mixing between the pump and resonant pulses of a degenerate femtosecond OPO provides an error signal suitable for actuating the cavity length with the precision needed to maintain oscillation on a single fringe and at maximum output power. Unlike commonly used dither-locking approaches, the method introduces no modulation noise and requires no additional optical components, except for one narrowband filter. The scheme is demonstrated on a Ti:sapphire-pumped sub-40-fs PPKTP OPO, from which data are presented showing a tenfold reduction in relative intensity noise compared with dither locking.

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Active phase control of a femtosecond optical parametric oscillator (OPO) in a way that stabilizes its comb-line positions requires cavity-length control with interferometric precision [1]. In nondegenerate systems, this can be achieved by monitoring a suitable beat frequency between the pump and signal/idler combs [2,3], but at degeneracy, the signal and idler beat frequencies become indistinguishable, with their values fixed at $f_{\mathrm{CEO}}^{P}/2$, where f_{CEO}^{P} is the offset frequency of the pump comb. In this regime, where the cavity length must be maintained at a value that is simultaneously resonant with the signal and idler comb modes, length changes of much less than one wavelength are observed not as a shift in the comb offset but as a variation in the output power of the OPO. Since the original demonstration in 2008 of robust degenerate operation of a femtosecond OPO [4], the dependence of the output power with cavity length has been used to stabilize such systems by dither locking, in which the resonator length is periodically swept through the position of maximum output power, providing the required asymmetric error signal by means of a lock-in detection technique. The principal embodiments of this method involve sweeping the pump [5] or OPO [6] cavity, which, as pointed out by Vainio and Halonen [7], introduces an instability in the comb teeth position or in the OPO output power. Neither is desirable for applications in which a high degree of OPO stability is required, but such approaches can be avoided in special cases by thermal locking [8], and more generally using a recently introduced scheme employing a long frequency-doubling crystal to upconvert and detect a portion of the OPO spectrum which varies sensitively to cavity length [7]. In this Letter, we show that stabilization can be realized at the peak of the OPO output by utilizing the always-present parasitic sum-frequency mixing (SFM) light between the pump and the resonant OPO pulses. This approach is shown to be simple and effective, achieving a tenfold lower relative intensity noise (RIN) than a dither lock applied to the same system, and requiring no more than the addition of a simple narrowband filter to extract the portion of the SFM spectrum that shows the greatest sensitivity to cavity length.

We demonstrated the stabilization concept using a Ti:sapphire-pumped PPKTP OPO, which is illustrated in Fig. 1, and similar to a system reported previously [9]. The pump laser produced 30 fs, 1 GHz pulses with an average power of 1 W and a center wavelength of 808 nm. The OPO was synchronously pumped by the Ti:sapphire laser, such that their round trip cavity lengths (300 mm) were equal. The OPO was a four-mirror ring resonator based around a 1.0 mm quasi-phase-matched PPKTP crystal with a domain period of 26.5 μm (Raicol Crystals) and which was cut at Brewster's angle. Pump light was coupled into the cavity through a 1% output coupler (OC). A pair of curved mirrors with a 20 mm radius of curvature (M1 and M2) was chosen such that a $1/e^2$ radius of 14 μm was achieved in the crystal. The pump beam was mode-matched to produce a 10 μm focal radius in the crystal. The folding angle of the curved mirrors was 7.5°, allowing for compensation of the astigmatism introduced by the Brewster-angled crystal. Mirror M3 was mounted on a piezoelectric transducer (PZT2) used

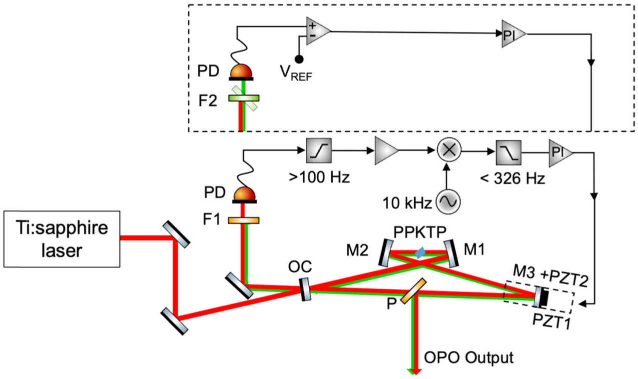

Fig. 1. Ti:sapphire-pumped degenerate OPO, with feedback electronics for conventional dither locking. Inset, optoelectronic scheme for side-of-fringe locking to the parasitic SFM light. Filter F1 rejects wavelengths < 1000 nm, while F2 is a 532 nm tunable filter with a 3 nm bandwidth.

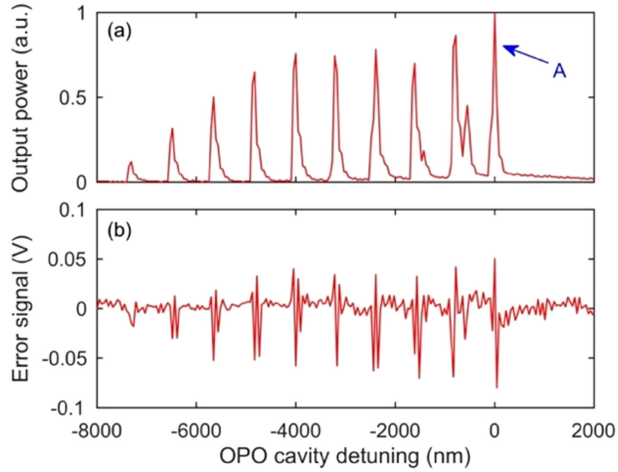

Fig. 2. (a) OPO output power and (b) derivative error signal obtained by dithering PZT2, recorded as the cavity was swept at 5 Hz using PZT1. When the locking loop was closed, the OPO was stabilized to peak A, which was the only peak corresponding to fully degenerate operation.

for dithering the cavity length, which in turn was mounted on a piezoelectric translation stage (PZT1) for cavity length adjustments. Mirror M1 was silver coated, allowing the pump beam to be focused directly into the crystal without using a lens. With the exception of the 1% output coupling mirror, the remaining OPO cavity mirrors had a dielectric coating, which transmitted the pump light and was highly reflective ($R > 99.9\%$) over the 1400–1800 nm region.

Before detailing the new dither-free locking scheme, we first present a characterization of the system configured using the conventional dither-locking approach (Fig. 1, main schematic), in which a local oscillator applied a small, 10 kHz modulation to PZT2. The OPO output power was sampled by a photodiode (PD), and this signal mixed with the local oscillator then was low-pass filtered to produce an error signal that actuated PZT1 after conditioning by a proportional-integral (PI) amplifier. The error signal obtained in this way is characterized by a steep gradient that passes through zero at the peak of the fringe, enabling locking at the maximum of the OPO output power (Fig. 2, peak A). Vainio and Halonen [7] observed that some midband wavelengths in the OPO spectrum vary sensitively to the cavity length near this maximum position, and this inspired their development of a dither-free scheme in which an independent narrow-bandwidth frequency-doubling crystal was used to convert a portion of the mid-IR signal/idler pulses to provide a near-IR signal with the behavior needed for cavity stabilization. We have found that an equivalent signal can be obtained by narrowband filtering of the parasitic output that is produced by the non-phase-matched SFM between the pump and OPO pulses. A parasitic SFM output is typically observed in all degenerate femtosecond OPOs, so its adoption into the stabilization scheme is general and easy to implement. Figure 3 shows the complete SFM spectrum (shaded) recorded when the OPO was operating at the peak of its output power, along with spectra measured after introducing an angle-tunable thin-film filter, whose maximum transmission at normal incidence was at 532 nm. Utilizing the SFM light as an error signal to stabilize the OPO at the peak of its output power requires that the SFM signal here is bidirectional, rising as the cavity length varies in one direction and falling as it moves in the other. This behavior is not observed for the entire SFM spectrum, but, as we show in

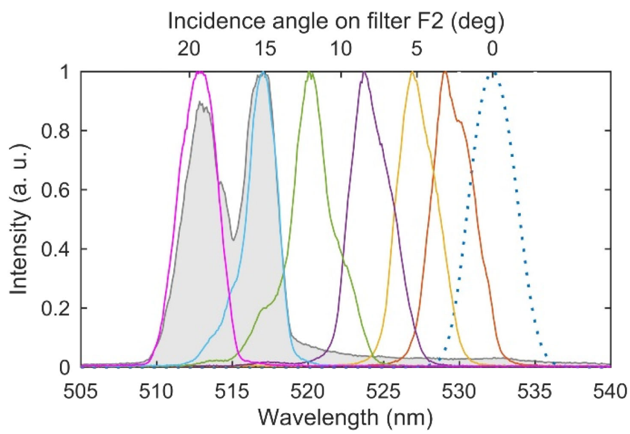

Fig. 3. Spectrum of the parasitic SFM from the OPO (shaded) along with the transmission profile of the 532 nm filter at normal incidence (dashed line). The remaining curves are the transmission spectra of the SFM light after the filter, recorded as the angle of the filter was detuned from normal incidence.

Fig. 4, an appropriately filtered portion of the SFM light does exhibit the necessary characteristics.

In Figs. 4(a)–4(d), we present the output power of the OPO as the cavity is swept across degenerate peak A and compare this with the power of four different spectrally filtered portions of the SFM light, recorded for increasing angles of incidence on the thin-film filter. The effect of tuning the filter can be seen as a shift in the relative alignment between the SFM error signal and the peak of the OPO fringe, allowing the locking to be configured at the maximum OPO output power. The multipeaked structures observed at small angles of incidence in Figs. 4(a)–4(c) correspond to the nonuniform spectral features apparent in the SFM spectrum shown in Fig. 3. When the filter was rotated to an angle of incidence of 19°, a uniform spectrum

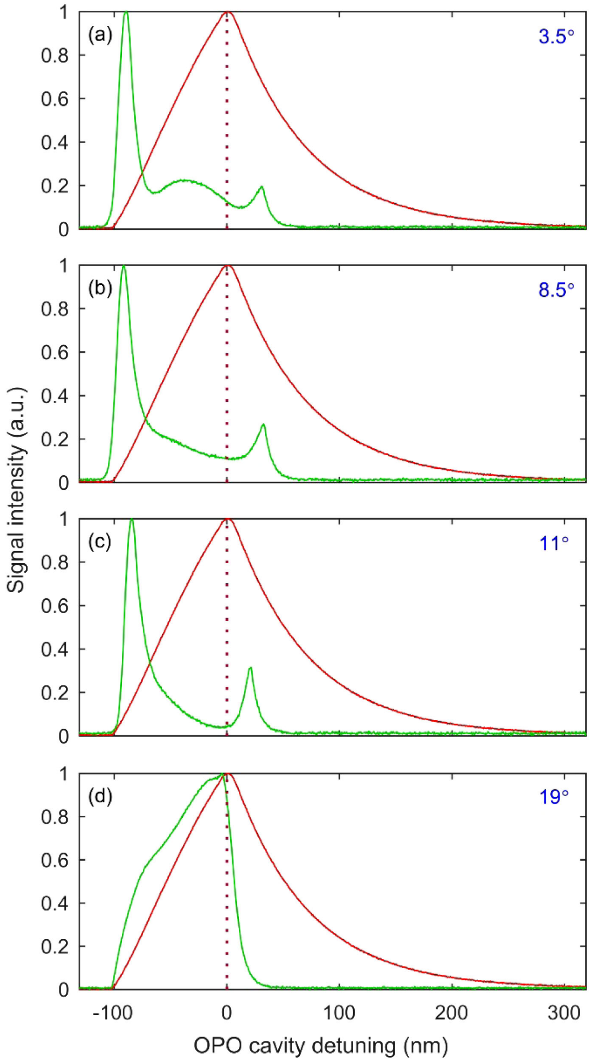

Fig. 4. Intensity of peak A of the OPO output at 1.6 μm (dashed red line) and the parasitic SFM output close to 520 nm (solid green line) as the angle of the interference filter was increased from 3.5° to 19°, in which the side of the SFM fringe is aligned with the center of the OPO fringe, enabling a side-of-fringe locking to the SFM light at this position.

was obtained, leading to a comparatively smooth signal containing a rapidly changing slope [Fig. 4(d)] suitable for stabilizing the OPO.

The inset in Fig. 1 shows how the dither-locked scheme was replaced by side-of-fringe locking on the SFM signal that stabilized the OPO at the maximum of its output power. A differencing amplifier was used to compare the SFM signal to a reference voltage, which was set to a value giving an error signal (the difference voltage) of zero when the OPO output power was a maximum. The error signal entered a PI amplifier, whose output was used to actuate PZT1 to achieve cavity-length stabilization. With the exception of a simple optical bandpass filter, this locking scheme introduces no additional elements to the system and eliminates much of the electronics or ancillary optical components associated with previously reported approaches.

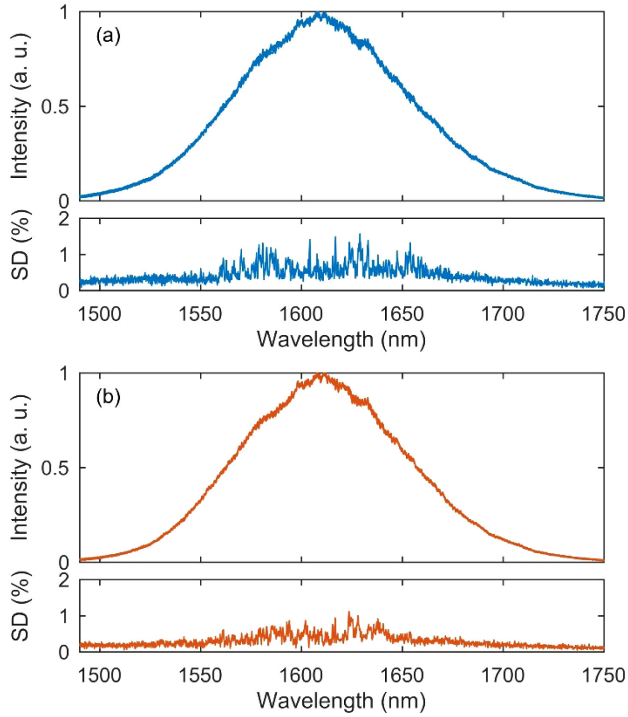

Fig. 5. Ten consecutive spectra recorded at 2 min intervals under (a) dither locking (blue) and (b) side-of-fringe SFM locking (red), with accompanying standard deviations.

We conducted a comparison of the performance obtained under the dither- and SFM-stabilization schemes. Locking was established on the same OPO oscillation fringe, with very similar spectra obtained under each scheme (see Fig. 5). The spectrum provided using side-of-fringe SFM locking was comparable in bandwidth to that obtained using dither locking. Ten consecutive spectra of the OPO output were recorded using both locking methods, with results shown in Fig. 5, displaying a maximum standard deviation in intensity across all wavelengths of 1.6% for dither locking and 1.1% for side-of-fringe SFM locking. The standard deviation of the FWHM of the spectrum for the SFM-stabilization scheme was 0.46%, similar to the 0.36% recorded for the dither-locking scheme. The same output power was achieved using both locking schemes, with the maximum value of 120 mW being consistent with previously reported results [9]. Cavity stabilization could be maintained for over an hour without interruption, during which we recorded a standard deviation of 0.11%, which is significantly lower than the 0.5% value measured for the dither-locked OPO.

In many applications, it is the noise performance of the OPO that is most critical. Using a fast PD, we recorded the RIN of the OPO under each locking configuration, and from this computed the power spectral density (PSD) of the noise, which we show in Fig. 6. As expected, the dither-locking scheme was dominated by the breakthrough of the 10 kHz modulation frequency, which is responsible for the majority of the noise, contributing to a cumulative RIN of 4.4% over a 1 s observation time. For other frequencies, the lock was relatively quiet, with only another 0.058% at lower frequencies and 0.132% contributed up to 32.8 kHz.

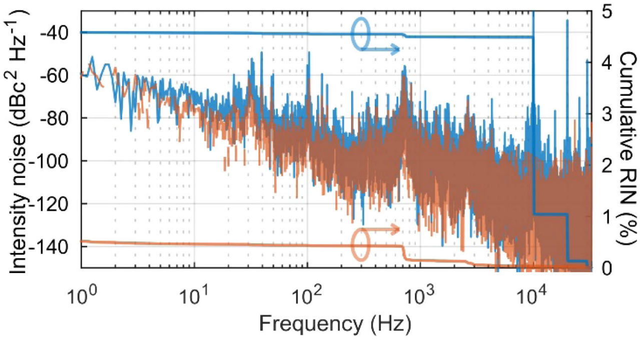

Fig. 6. Comparison of relative intensity noise recorded on the OPO output under dither locking (blue) and side-of-fringe SFM locking (red).

With side-of-fringe SFM locking, the cumulative noise was less than 0.4% across all frequencies, a more than tenfold reduction in RIN compared with dither locking. For both the dither- and side-of-fringe locking schemes, the majority of the residual noise is believed to originate from environmental noise at frequencies above the bandwidth of PZT1, and from resonances in the stage itself.

In summary, we have demonstrated a new approach to the stabilization of a degenerate femtosecond OPO that exploits the parasitic SFM between the pump and OPO pulses to provide an error signal suitable for actuating the resonator with the precision needed to maintain oscillation on the peak of the strongest oscillation fringe. Unlike commonly used dither-locking schemes, the method introduces no modulation noise and requires no additional optical components, except for one narrowband filter. The technique we have introduced shows a noise performance equal to that of the best previously reported results from a degenerate OPO [7]. An application that we anticipate benefiting from this modulation-free locking is where the OPO comb modes will be further operated on by an additional locked cavity. In our intended application of the OPO as part of an astrocomb system [10], a Fabry–Perot etalon will be locked directly to the comb, as has been reported already for mode filtering of a Ti:sapphire supercontinuum from 1 GHz to > 15 GHz [11]. Here, dither locking of both the OPO and the subsequent Fabry–Perot cavity would result in complications associated with cross talk between the two dither frequencies; this issue is avoided by the adoption of a modulation-free locking scheme for the OPO.

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